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Do Mergers Spin Up Dark Matter Halos?

Elena D'Onghia[1]⋆ & Julio F. Navarro[2]†
[1] *Institute for Theoretical Physics, University of Zurich, Winterthurerstrasse 190, CH-8057 Zurich, Switzerland*
[2] *Department of Physics and Astronomy, University of Victoria, 3800 Finnerty Road, Victoria, BC, Canada V8P 5C2*

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ABSTRACT
We use a large cosmological N-body simulation to study the origin of possible correlations between the merging history and spin of cold dark matter halos. In particular, we examine claims that remnants of major mergers tend to have higher-than-average spins, and find that the effect is driven largely by unrelaxed systems: equilibrium dark matter halos show no significant correlation between spin and merger history. Out-of-equilibrium halos have, on average, higher spins than relaxed systems, suggesting that the virialization process leads to a net decrease in the value of the spin parameter. We find that this decrease is driven by the internal redistribution of mass and angular momentum that occurs during virialization, a process that is especially efficient during major mergers, when high angular momentum material is pushed beyond the virial radius of the remnant. Since such redistribution likely affects the angular momentum of baryons and dark matter unevenly, our findings question the common practice of identifying the specific angular momentum content of a halo with that of its embedded luminous component. Further work is needed to elucidate the true relation between the angular momentum content of baryons and dark matter in galaxy systems assembled hierarchically.

Key words: galaxies: formation – galaxies: halos – galaxies: structure – cosmology: theory – dark matter – large-scale structure of Universe – methods: numerical, N-body simulation

1 INTRODUCTION

The angular momentum of a galactic system has long been thought of as a crucial ingredient of the cosmic recipe that governs the formation and evolution of galaxies. In the current paradigm, the net spin of a dark matter halo and of its luminous component originates in torques exerted by neighbouring structures at early times. This tidal-torque theory, proposed by Hoyle (1949) and developed by Peebles (1969) and White (1984), envisions the spin of a halo as acquired during the early expansion phase, when tides are strong and when the moment of inertia of the material destined to collapse is large.

The acquisition of angular momentum abates after turnaround, as the moment of inertia of the collapsing material decreases and the universal expansion pushes the neighbouring matter responsible for tides ever farther, effectively arresting any further increase in net angular momentum. In the absence of dissipation, and for reasonably isolated systems, energy and angular momentum are conserved during the subsequent collapse and virialization, so the spin of a dark matter halo is effectively set at turnaround and should evolve little thereafter (see Porciani et al. 2002a,b for a review of this and more recent work).

This scenario has interesting and testable consequences. Tidal torques generate net angular momentum principally through the misalignment between the gravitational (tidal) shear tensor and the inertia tensor of the material being spun up. These misalignments are generally rather weak, making the spin-up process rather inefficient and leading to a fairly broad distribution of halo spins peaked well below the values needed for substantial centrifugal support (Porciani et al. 2002b).

Numerical simulations confirm this expectation: the spin distribution of collapsed structures, as measured by the dimensionless spin parameter, $\lambda = J|E|^{1/2}/GM^{5/2}$ (J is the angular momentum, E is the binding energy, and M is the total mass of a halo), is wide and has a median value of $\lambda_{\rm med} \approx 0.035$ (see, e.g., Bullock et al. 2001, Gardner (2001), D'Onghia & Burkert 2004, Maccio' et al. 2006, Bett et al. 2007). The rather poor efficiency of the spin-up process is also thought to explain the extremely weak—but discernible—correlations between λ and other halo proper-

⋆ Marie Curie Fellow; Email: elena@physik.unizh.ch
† CIAR and Guggenheim Fellow

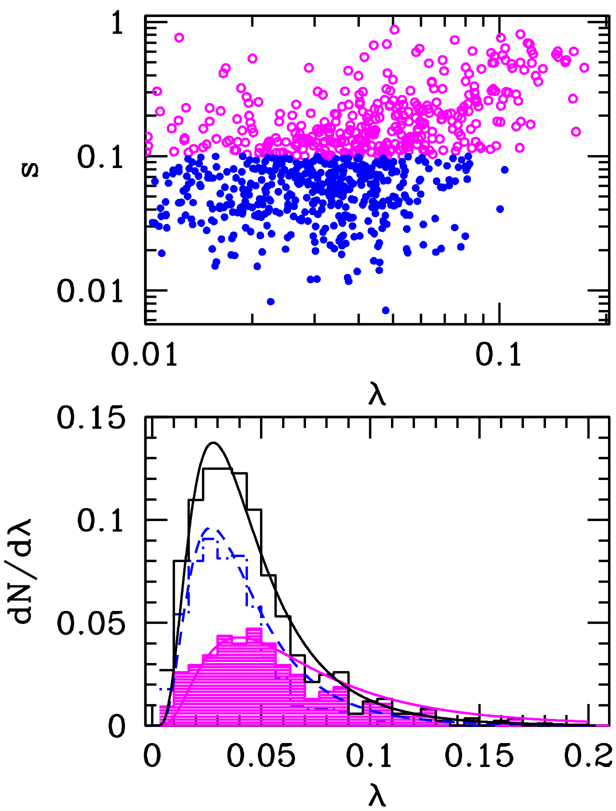

Figure 1. *Top panel:* The off-center parameter, s, versus the spin parameter, λ, measured within the virial radius at $z = 0$ for all halos in our sample. Open circles correspond to "unrelaxed" systems ($s > 0.1$); typically the remnants of recent accretion events and mergers. Filled circles ($s < 0.1$) denote "relaxed" systems closer to virial equilibrium. *Bottom panel:* The distribution of spin parameters of all halos (top histogram), "relaxed" halos ($s < 0.1$, dot-dashed histogram), and "unrelaxed" systems ($s > 0.1$, shaded histogram). Curves show best lognormal fits to each histogram; fit parameters are listed in the text.

ties such as mass, formation time, and environment (Lemson & Kauffmann 1999; Avila-Reese et al. 2005; Allgood et al. 2006; Shaw et al. 2006; Hahn et al. 2007).

The tidal-torque scenario also implies that the specific angular momentum acquired by the baryonic and dark matter components of a galaxy should be similar, since the acquisition predates the collapse of the system, during which non-linear effects may result in substantial transfer of energy and angular momentum between the two components (Navarro & Benz 1991; Navarro & White 1994; Navarro & Steinmetz 1997, D'Onghia et al. 2006, Kaufmann et al. 2007). This result underpins the assumptions of semianalytic work on galaxy formation where the angular momentum of a luminous galaxy is often drawn randomly from the spin distribution of dark matter halos obtained from cosmological N-body simulations (see, e.g., Cole et al 2000 and references therein).

Recently, however, a number of authors have highlighted the possibility that mergers may play a substantial role in determining the angular momentum content of a dark matter halo. D'Onghia & Burkert (2004), for example, argue that halos with a quiet merging history might not acquire enough angular momentum to host late-type spiral galaxies. Gardner (2001), Vitvitska et al. (2002), and Hetznecker & Burkert (2006), among others, report a significant correlation between mergers and spin and ascribe it to the large orbital angular momentum associated with major mergers. Vitvitska et al (2002), in particular, follow the evolution of the spin parameter of the *most massive progenitor* of several dark halos and find that the spin parameter varies with time, increasing abruptly during major mergers, and decreasing gradually during times of minor accretion.

This is an intriguing result, since late major mergers are normally thought to be associated with the formation of elliptical galaxies (see, e.g., the review by Burkert & Naab 2003), which have long been known to be—at fixed stellar mass—deficient in angular momentum relative to spirals (Fall 1983). It is puzzling (and counterintuitive) that galaxies where rotational support is low should tend to inhabit dark halos where angular momentum is more plentiful.

We note, however, that the evolution of the spin of the most massive progenitor of a halo might not be a faithful and direct measure of the available angular momentum. Indeed, λ is a *dimensionless* rotation measure most useful for *isolated* systems (where E, J, and M are conserved), but of suspect applicability during a major merger, when the identity of the system varies dramatically with time.

On the other hand, angular momentum (total or specific) is a *dimensional* quantity that typically increases as the mass and size of a halo grow (see, e.g., Figure 8 of Navarro & Steinmetz 1997). Late major-merger remnants are, by definition, halos where a significant amount of mass (and, in general, of angular momentum) has been recently added to the halo. These late-assembling systems must have "turned around" later than an average halo of comparable mass. One might therefore expect that tides have had a chance to operate for a longer period of time, which may explain their higher-than-average spins.

Is this why merger remnants are reported to have higher-than-average spins? Or do major merger remnants have instead spins comparable to those of halos that have accreted a similar amount of mass on a similar timescale through mainly smooth accretion? A proper answer to these questions should evaluate the effect of mergers on halo spin separately from the role of accretion, taking special care to define the boundaries of the system so that spin measures are robust and meaningful.

These are the issues that we address in this *Letter*. In § 2 we present details of the numerical simulation and analysis procedure. § 3 discusses our main results, whilst § 4 summarizes our conclusions and implications.

2 NUMERICAL METHODS

2.1 Simulations

We analyze a cosmological N-body simulation of the ΛCDM cosmogony, with cosmological parameters chosen to match the WMAP3 constraints (Spergel et al. 2006). These are characterized by the present-day matter density parameter, $\Omega_0 = 0.238$; a cosmological constant contribution, Ω_Λ=0.762; and a Hubble parameter $h = 0.73$ ($H_0 = 100\,h$

km s^{-1} Mpc^{-1}). The mass perturbation spectrum has a spectral index, $n = 0.951$, and is normalized by the linear rms fluctuation on 8 Mpc/h radius spheres, $\sigma_8 = 0.75$.

We simulate the evolution of 400^3 particles of mass $m_{\rm dm} = 1.2 \times 10^8\, h^{-1}\, M_\odot$ in a box 50 h^{-1} Mpc (comoving) on a side using the publicly available code GADGET2 (Springel 2005). Gravitational interactions between pairs of particles are softened by a spline kernel with fixed comoving Plummer–equivalent length of 3 h^{-1} kpc.

2.2 Halo identification

Non-linear structures at $z = 0$ are identified using the classic friends-of-friends (FOF) algorithm with a linking length equal to 0.2 times the mean interparticle separation. For each FOF halo we identify the most bound particle and adopt its position as the halo center. Using this center, we compute the "virial radius" of each halo, $r_{\rm vir}$, defined as the radius of a sphere of overdensity $\Delta(z = 0) = 94$ (relative to the critical density for closure)[1]. Quantities measured within $r_{\rm vir}$ will be referred to as "virial", for short. We select for our analysis all halos with masses in the range $M_{\rm vir} = 5 \times 10^{11}$ to $10^{13}\, h^{-1}$ $M_\odot$, resulting in 848 halos with $N_{\rm vir}$ betweeen $5,000$ and $80,000$ particles.

The assembly history of each halo may be studied using halo catalogs analogous to the one just described, but constructed at various times during the evolution of the system. For the purposes of our analysis, we concentrate on the period $0 < z < 3$. Halos identified at $z > 0$ are said to be *progenitors* of a $z = 0$ system if at least 50% of its particles are found within the virial radius of the latter. Using this definition we can identify, at all times, the list of progenitors of a given $z = 0$ halo and track their properties through time.

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2.3 Halo properties

We compute, for all halos identified at $z = 0$, the spin parameter λ, using all particles within the virial radius. Note that this choice defines implicitly the mass of the halo and its angular momentum, and that the values of the spin parameters assigned to a halo may be sensitive to this choice. Especially sensitive will be halos that are ostensibly out of equilibrium, since the virialization process will then lead to rapid changes in the values of the virial radius, mass, and angular momentum that define λ.

[1] The virial overdensity in a flat universe may be computed using the fitting formula proposed by Bryan & Norman (1998): $\Delta(z) = 18\pi^2 + 82\, f(z) - 39\, f(z)^2$; with $f(z) = \frac{\Omega_0(1+z)^3}{\Omega_0(1+z)^3+\Omega_\Lambda} - 1$

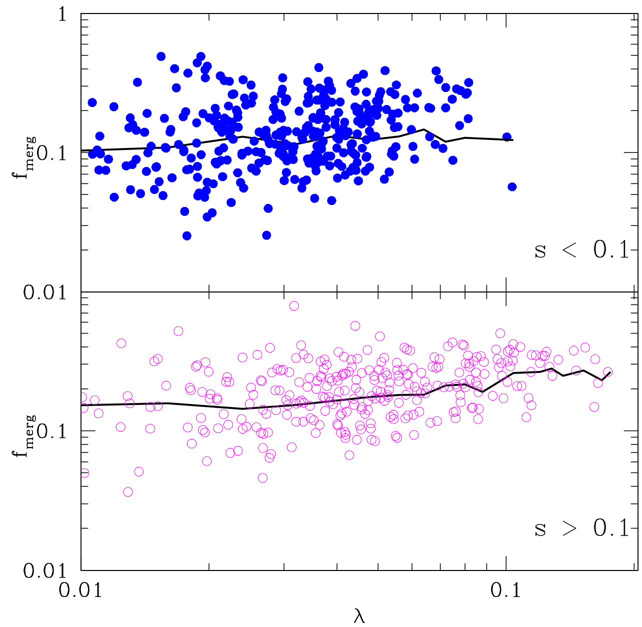

Figure 2. The fraction of mass, $f_{\rm merg}$, accreted by a halo in the single most important merger event since $z = 3$, versus the spin parameter, λ, measured within the virial radius at $z = 0$ for each halo in our sample. Top and bottom panels correspond to "relaxed" and "unrelaxed" halos, respectively.

In order to assess these effects, we compute, for each halo, the distance from the most bound particle to the center of mass of the halo, normalized by the virial radius. This "off-center" parameter, $s = |\mathbf{r}_{\rm cm} - \mathbf{r}_{\rm mb}|/r_{\rm vir}$, is a simple but telling measure of the prevalence of unrelaxed substructure within the halo and, consequently, of its equilibrium status. As discussed, for example, by Hetznecker & Burkert (2006), Maccio' et al. (2006), and Bett et al (2007), halos with $s > 0.1$ are remnants of relatively recent accretion events which are still undergoing rapid changes in their structural properties. Halos with $s < 0.1$ are generally closer to virial equilibrium and evolve weakly with time. Some exceptions do occur, since ongoing mergers may by chance have (briefly) $s < 0.1$, but these exceptions are rare.

The importance of mergers during the assembly of the halo may be estimated by the fraction of the mass contributed by the largest accretion event in the assembly history of the halo, and is measured in our analysis by the mass of the largest 2nd most massive progenitor of a halo,

$$f_{\rm merg} = \frac{M_{\rm 2nd}(z < 3)}{M_{\rm vir}(z = 0)}, \quad (1)$$

identified since $z = 3$, and normalized to the present-day virial mass of the halo.

3 RESULTS

3.1 Spin distribution and virial equilibrium

The spin distribution of all halos selected at $z = 0$ is shown by the top histogram in the bottom panel of Figure 1, and may be approximated by a lognormal distribution,

$$p(\lambda)\,\mathrm{d}\lambda = \frac{1}{\sigma_\lambda\sqrt{2\pi}}\exp\Big[-\frac{\ln^2(\lambda/\bar{\lambda})}{2\sigma_\lambda^2}\Big]\frac{\mathrm{d}\lambda}{\lambda}, \qquad (2)$$

with $\bar{\lambda}\sim 0.03$ and $\sigma_\lambda = 0.58$, consistent with previous work on the subject (Avila-Reese et al. 2005; Allgood et al. 2006; Shaw et al. 2006; Maccio' et al. 2006; Bett et al. 2007). This fit is shown by the thick solid line in the same panel.

The other two histograms in the bottom panel of Figure 1 correspond to splitting the halo sample according to the offset parameter s. "Unrelaxed" halos (i.e., those with $s > 0.1$, shaded histogram) make up 46% of the sample, and tend to have higher-than-average spins. "Relaxed" halos (i.e., those with $s < 0.1$; dot-dashed histogram) have a narrower λ distribution more sharply peaked around slower rotators. This difference is reflected in the parameters of the best lognormal fits to each histogram, which give $\bar{\lambda}$=0.028 and $\sigma_\lambda = 0.58$ for relaxed halos, and $\bar{\lambda}$=0.04 and $\sigma_\lambda = 0.65$ for unrelaxed systems.

The difference in the spin of relaxed and unrelaxed halos is responsible for the clear trend between s and λ seen in the top panel of Figure 1. The majority of slowly-rotating halos are in equilibrium: 71% of halos with $\lambda < 0.02$ have $s < 0.1$. This fraction drops to 59% for halos with $0.03 < \lambda < 0.06$, and there are basically no equilibrium halos with $\lambda > 0.1$. Since the remnants of recent major mergers undoubtedly figure prominently in the unrelaxed halo sample, the trend apparent in the top panel of Figure 1 is reminiscent of the findings of Gardner (2001), Vitvitska et al. (2002) referred to in § 1.

3.2 Mergers and spin

The relation between mergers and spin is explored in Figure 2, where the top panel show, for relaxed ($s < 0.1$) halos, the dependence of the spin parameter on $f_{\rm merg}$, the fraction of mass accreted by a halo in its single most important merger event since $z = 3$. This panel show that there is no statistically significant correlation between λ and merger activity when considering systems near virial equilibrium. The visual impression is confirmed by the nearly horizontal line in the top panel that traces the median value of $f_{\rm merg}$ as a function of λ.

Note that the relaxed halo sample includes many remnants of major merger events; 13% of them have accreted more than 25% of their mass in a single merger, and half of them have undergone at least one merger during which more than $\sim 15\%$ of their final mass was accreted. Yet, there is no obvious evidence that more massive mergers lead to higher than average spin parameters. *We conclude that merging history and spin are largely uncorrelated in equilibrium halos.*

The bottom panel of Figure 2 extends this analysis to "unrelaxed" halos, and show that, although a similar conclusion holds for the bulk of the sample, there is a high-spin ($\lambda > 0.1$) tail in the distribution that is almost exclusively populated by systems that have added at least $\sim 30\%$ of their mass in relatively recent merger events. Because these systems are out of equilibrium, spin estimates are likely to fluctuate as they relax, mostly as a result of the evolving boundaries of the system imposed by the virial definitions discussed in §2.2. These fluctuations must lead to a net overall reduction in the spin measured within the virial radius

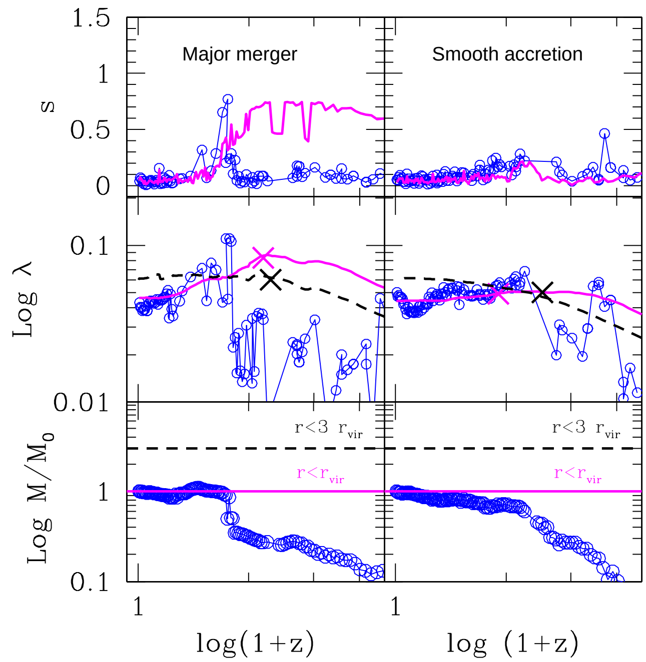

Figure 3. Evolution of the off-center parameter, s, the spin parameter, λ, and the mass, M, for two halos chosen to have a similar value of λ and to be in equilibrium at $z = 0$. Masses are scaled to the virial mass of each halo at $z = 0$. The halos differ in their merging history. One of the halos (left panels) undergoes a major merger at $z = 0.7$ ($f_{\rm merg} = 0.36$), whereas the other (right panels) has a smoother accretion history ($f_{\rm merg} = 0.07$). Open circles correspond to the most massive progenitor of the halo, whereas solid and dashed lines correspond, respectively, to *all* particles identified within one and three times the virial radius at $z = 0$.

in order to explain the difference in the spin distribution of relaxed and unrelaxed halos shown in Figure 1.

3.3 Spin evolution

We explore this in Figure 3, where we follow the evolution of two halos selected to have similar spin ($\lambda = 0.045$) and to be in equilibrium (i.e., $s < 0.1$) at $z = 0$, but of very different merger history. One of them (shown in the left panels of Figure 3) has seen a large fraction of its mass accreted in a major accretion event ($f_{\rm merg} = 0.36$), whereas the other (right-hand panels) has had a much smoother accretion history ($f_{\rm merg} = 0.07$).

Open circles in this figure correspond to the most massive progenitor identified at each redshift. In the case of the major merger remnant, its mass more than doubles between $z \sim 0.8$ and $z \sim 0.7$. Subsequent evolution adds little extra mass to the system, which gradually relaxes into equilibrium: the center offset parameter, s, drops from a maximum of about unity at the height of the merger ($z \sim 0.75$) to $s < 0.1$ by $z \sim 0.3$, and it remains in that range until the present.

For this halo, the evolution of the spin parameter of the most massive progenitor evokes the results of Vitvitska et al (2002): λ rises during the merger to $\lambda \sim 0.1$ and then drops gradually to its final value of $\lambda = 0.045$ at $z = 0$.

Since energy and angular momentum are conserved in collisionless mergers, the net reduction in spin must occur as a result of the internal redistribution of mass and angular momentum ensuing the merger. This process tends to populate the central regions of the remnant with low-angular momentum material and to push high angular momentum particles into weakly bound orbits. As a result, the spin measured *within* the (evolving) virial radius of the halo steadily drops although the *total* energy and angular momentum of the system is conserved.

This may be seen by following the spin parameter measured over a larger volume that includes the halo. The solid and dashed lines without symbols in Figure 3 correspond, respectively, to *all* particles that end up, at $z = 0$, within one and three virial radii from the center of the halo. The comparison between these two curves show that, when measured over an expanded region not subject to arbitrary "virial" boundaries, the time evolution of the spin parameter follows closely the behaviour expected from tidal torque theory: net spin is acquired early and evolves little after turnaround[2].

In particular, the dashed line in the mid-panel of Figure 3 shows that the spin of the larger region where the halo is embedded is acquired well before the merger takes place, and remains constant after turnaround at $z = 1.3$ despite the major merger event at $z = 0.73$. The merger-induced spin-up and subsequent spin-down of the most massive progenitor during a merger is thus clearly a result of restricting the computation of mass, energy, and angular momentum to a subset of the system, namely that contained within the evolving virial radius of the halo—i.e., the most massive progenitor. Although we have chosen a particular halo for illustration in the left panels of Figure 3, we have explicitly checked that similar results are consistently found when applying this analysis to all major merger remnants.

Similar results are found for systems that have been assembled through smoother accretion merging histories (right-hand panels in Figure 3) Here again, and despite the large differences in merging activity, the spin parameter of the region where the halo is embedded is fixed at turnaround and remains approximately constant thereafter. Interestingly, the after-merger spin-down of the most massive progenitor is not obvious here, implying that the redistribution of angular momentum from the center outwards responsible for that drop is most efficient during major mergers.

4 SUMMARY

We have used numerical simulations to examine the relation between the merger history and spin of cold dark matter halos. Our results show that, as expected from standard tidal torque theory, the angular momentum of the material destined to collapse into a halo is acquired during the early expansion phase and evolves little after turnaround, regardless of whether the subsequent assembly of the halo involves mainly major mergers or smooth accretion. Major mergers, *per se*, do not result in higher-than-average spins: we fail to find a significant correlation between merger history and halo spin in equilibrium halos.

Unrelaxed halos, on the other hand, do have a spin distribution that peaks at higher values than equilibrium systems. Since these halos must eventually relax, this result implies that virialization leads in general to a net reduction in the spin of a system. We show that this results from the redistribution of matter and angular momentum that accompanies virialization, a process that may push high angular momentum material outside the virial radius of a halo and that is especially efficient during major mergers.

These results call into question the common practice of assuming that there is a tight correspondence between the angular momentum of a halo (measured within its virial radius and without regard for its equilibrium status) and that of its baryonic component. Baryons and dark matter will be affected differently by the redistribution of angular momentum that occurs during virialization, depending largely on the spatial segregation of one component relative to the other. The more segregated the baryons are before the assembly of the system is completed, the more angular momentum they will tend to transfer to the dark matter as they spiral to the center to form the final system. The efficiency of this process is likely to vary strongly with merger history; to affect most prominently the remnants of recent major mergers; and to result, overall, in a rather complex relation between the angular momentum of a halo and that available to its luminous, baryonic component. Only simulations that follow, in a realistic manner, the cooling and condensation of the baryons within the multiple stages of the hierarchical assembly of a galaxy system are likely to capture the true interdependence between spin and assembly history of a galaxy.

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REFERENCES

Allgood B., Flores R., Primack J. R., Kravtsov A. V., Wechsler R. H., Faltenbacher A., Bullock J. S. 2006, MNRAS, 367, 1781
Avila-Reese V., Colín P., Gottloeber S., Firmani C., Maulbetsch C. 2005, ApJ, 634, 51
Bett P., Eke V., Frenk C. S., Jenkins A., Helly J., Navarro J. 2007, MNRAS, in press (astro-ph/0608607)
Bryan G., Norman M. 1998, ApJ, 495, 80
Bullock J. S., Dekel A., Kolatt T. S., Kravtsov A. V., Klypin A. A., Porciani C., Primack J. R. 2001, ApJ, 555, 240

[2] This is defined as the time when the moment of inertia of each subset of particles peaks and is marked by a cross on each curve.

Burkert, A. & Naab, T. 2003, in Galaxies and Chaos,eds. G. Contopoulos & N. Voglis, Springer, p. 327
Cole, S., Lacey, C. G., Baugh, C. M., & Frenk, C. S. 2000, MNRAS, 319, 168
D'Onghia E., Burkert A. 2004, ApJ, 612, L13
D'Onghia, E., Burkert, A., Murante, G., Khochfar, S. 2006, MNRAS, 372, 1525
Fall, S. M. 1983, IAU Symp. 100: Internal Kinematics and Dynamics of Galaxies, 100, 391
Gardner J.P. 2001, ApJ, 557, 616
Hahn, O., Porciani, C., Carollo, M., Dekel, A. 2007, MNRAS, 375, 489
Hetznecker H., Burkert A. 2006, MNRAS, 370, 1905
Hoyle F. 1949, in Problems of Cosmical Aerodynamics (Dayton, Ohio: Central Air Documents Office), p.195 ApJ, 532, L5
Kaufmann T., Mayer L., Wadsley J., Stadel J. & Moore B. 2007, MNRAS, 375, 53
Lemson G., Kauffmann G. 1999, MNRAS, 302, 111
Maccio' A., Dutton A., van den Bosch F., Moore B., Potter D., Stadel J. 2006, MNRAS, submitted (astro-ph/0608157)
Navarro, J.F., Benz, W. 1991, ApJ, 380, 320
Navarro J. F., White S. D. M. 1994, MNRAS, 267, 401
Navarro J. F., Steinmetz M. 1997, ApJ, 478, 13
Peebles P. J. E. 1969, ApJ, 155, 393
Porciani C., Dekel A., Hoffman Y. 2002a, MNRAS, 332, 325
Porciani C., Dekel A., Hoffman Y. 2002a, MNRAS, 332, 339
Shaw L., Weller J., Ostriker J. P., Bode P. 2006, ApJ, 646, 815
Spergel, D. N., et al. 2006, astro-ph/0603449
Springel V. 2005, MNRAS, 999
Vitvitska M., Klypin A. A., Kravtsov A. V., Wechsler R. H., Primack J. R., Bullock J. S. 2002, ApJ, 581, 799
White S. D. M 1984, ApJ, 286, 38